

Article

Assessing Risk and Prioritizing Safety Interventions in Human Settlements Affected by Large Wildfires

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Abstract: The large wildfires of June 2017 disturbed many communities in central Portugal. The civil parish of Alvares was severely affected, with about 60% of its area burnt. Assessing the risk of large wildfires affecting local communities is becoming increasingly important, to reduce potential losses in the future. In this study, we assessed wildfire risk for the 36 villages of Alvares parish, by combining hazard, exposure and vulnerability analysis at the settlement scale. Hazard was obtained from fire spread simulations, which integrated exposure together with population and building density within each village. Vulnerability was based on the sociodemographic characteristics of the population, ranked with a hierarchical cluster analysis. Coping capacity was also integrated, considering the distance of each village to the fire station and the time needed for residents to reach a shelter. We simulated 12 different land management scenarios, regarding the implementation of a fuel-break network and the level of forest management activities. The potential effects of each scenario in the exposure and risk levels of the settlements were evaluated. The results show that, for a business-as-usual scenario, 36% of the villages are at high or very high risk of wildfires. Examining each risk component, 28% of the villages are highly exposed, 44% are highly vulnerable, and 22% do not have a potential shelter on-site, calling for different intervention strategies in each specific risk dimension. All the land management scenarios, even if designed for other purposes than the protection of settlements, could decrease the proportion of highly exposed villages at different levels, up to a maximum of 61%. These findings can contribute to adjust prevention and mitigation strategies to the risk levels and the characteristics of the population and the territory, and to prioritize the protection and emergency actions at the local scale.

Keywords: wildfire risk; vulnerability assessment; forest management; coping capacity; protection of villages; local scale

1. Introduction

In many ecosystems, fire is an inevitable process that coexists with human communities [1,2], but the negative effects of wildfires have increased over the last decades [3]. Wildfire disasters causing huge impacts and human losses occurred recently in different parts of the world, such as Australia, California, Chile, Greece, and Portugal [4–7]. Threats to human safety and property are a major challenge to wildfire management and, in most countries, their protection is a responsibility that falls primarily on government agencies [8,9]. Often, firefighting options prioritize the protection of people first, and the defence of built-up structures. However, the unprecedented dimension of wildfires and their massive negative impacts highlight the need to enhance the institutional capacity and to reinforce other

protection mechanisms, since available suppression and emergency resources will likely be outstripped in fire-prone environments [10]. These settings are expected to further exacerbate in the future due to ongoing unfavourable sociodemographic changes, to the expansion of the Wildland-Urban Interface (WUI), and to the effects of climate change [11–16].

Recent wildfire disasters have spurred studies on alternative strategies to reduce wildfire impacts, focusing on the individual behaviour of exposed people and on the options available for local communities. The implementation of protective actions by residents is one approach, implying the intervention of homeowners by using non-flammable building materials and clearing vegetation around their houses [17–19]. Other approaches are based on evacuation options and on resorting to local shelter possibilities, when fleeing the site is not possible or advisable [20–25]. The mitigation strategies applied will largely depend on the characteristics of the residents and on the dynamics of local communities, which determine the ability to anticipate, prepare, and respond to a potential disastrous event [8,10,26–30]. Previous experience, financial capacity, demographics, and perceived risk shape the response to a threat and define the level of vulnerability of a person and a community with regard to the impacts caused by a hazardous event [9,31–34].

Vulnerability assessment characterizes the potential for loss and is based on the sociodemographic attributes of people and their living conditions. For example, low economic capability, advanced age, or low education level can lead to high vulnerability [9,35–37], meaning that these people are less able to cope with the impacts and recover from the consequences of a hazard. Vulnerability is analysed in relation to wildfire exposure, which takes into account the type and density of people and assets present in hazardous areas [36,38], the historical fire data [37], and/or simulations of potential fires under particular weather and fuel conditions [10,38–42]. The combination of hazard, exposure, and vulnerability gives the level of risk, understood as the probability of occurrence of a fire in a certain area and its potential consequences [43,44]. Wildfire risk assessment provides an integrated view of the different factors that frame wildfire incidence, and evaluates the relative contribution of each risk component (hazard, exposure, and vulnerability), thereby supporting wildfire management decision-making.

The Wildfires of 2017 in Portugal—The Case of Alvares

The year of 2017 was the worst ever in Portugal regarding wildfires. In comparison with the previous 40 years, the country suffered the largest burned area, of about 500,000 ha, and the highest number of fatalities ever recorded, with 112 people deceased [45]. These fires were influenced by abnormal weather conditions that occurred in Southern Europe that year; drought, heatwaves, and storms fueled extreme fires that strongly affected central Portugal, outside the main fire season, specifically in June and October. These climatic conditions are expected to repeat in the future and cause likewise events; therefore, fire risk in the region will likely increase [46–48].

In mid-June 2017, the civil parish of Alvares, in the municipality of Góis, was struck by a large wildfire that destroyed 6000 ha, equivalent to about 60% of the parish total area. In the adjacent area of Pedrógão Grande, another fire occurred at the same time and, together, these wildfires burned 45,000 ha. The 2017 wildfire was the most recent of 42 events that affected the civil parish of Alvares in the last 40 years and burned 20,000 ha, equivalent to twice the parish total area. About 90% of the total burnt area extent resulted from 10 wildfires larger than 1000 ha each. Several factors explain the historical background of wildfire occurrence in this parish, which are similar to other areas in central Portugal: (i) the increase in forested area over the last 100 years, from 10% to 90% of the parish area, resulting in a closed and continuous landscape, mostly composed of eucalypt and pine stands; (ii) the land abandonment and population aging trends, with a loss of 75% of the population since 1960, and a current demographic situation where nearly half the residents are over 65 years old; (iii) the lack of forest management and the small size of the properties (0.5 ha on average), with land parcels scattered over more than 3000 owners only in this parish [49]. There were high environmental and economic damages but no human losses; when the parish was being struck by the wildfire, and despite the lack

of official evacuation protocols, the firefighters and local authorities evacuated the residents of some of the villages on a voluntary basis, gathering people in the fire station of the main settlement.

In the aftermath of the 2017 fires, a group of local landowners who intended to create a Forest Intervention Zone (ZIF) [50], requested aid from the University of Lisbon to implement suitable wildfire mitigation measures and prevent further losses in the future. The project “Alvares—a case of resilience to fire”, was then created, with funding from a private media group that owns the electronic newspaper “Observador”, and carried out by a multidisciplinary team led by the Forest Research Centre (CEF), School of Agriculture (ISA). The goal was to develop proposals to increase the resilience of the Alvares parish to wildfires, based on three pillars: (1) to reduce the frequency of large fires; (2) to improve the safety of people and the protection of assets; and (3) to strengthen the local economy. The main aim was to identify the necessary steps to pursue the social, economic, and environmental sustainability of Alvares, with a procedure suitable for scaling up to other fire-prone areas of Portugal.

In this study, we focused on the second pillar of the project, the protection of people and assets. We combined fire spread simulation modeling with geospatial and statistical information to assess wildfire exposure, vulnerability, and risk levels of the human settlements located in the parish. To our knowledge, this is the first attempt to assess risk and its components at such fine scale in the country. This option was driven, on the one hand, by the influence of the local context in people’s response to wildfires and, on the other hand, by the need to deliver knowledge and tools that could be used at the operational level to improve the protection of settlements. The main purpose was to obtain a ranking system for the existing settlements concerning wildfire risk levels that could help prioritize safety interventions and mitigation actions. In addition, we analyzed how different options, regarding fuel break implementation and forest management in neighboring land, could change the exposure and risk levels of human settlements.

After the wildfires of 2017, new legislation was approved in Portugal to promote the implementation of safety initiatives and self-protection measures in local communities (Resolution of the Council of Ministers, RCM 157-A, 27 October 2017). One of these initiatives focuses specifically on the protection of human settlements by establishing shelters and evacuation protocols for residents, called “Safe Villages, Safe People” (free translation of the original denomination “Aldeias Seguras, Pessoas Seguras”), a programme managed by the National Authority for Civil Protection and Emergencies. The launch of this programme coincided with the timeframe of this research and, since the objectives of the initiative were parallel to our scientific purposes, we included the definition of shelter areas and the analysis of the evacuation time in the risk assessment procedure, as a coping capacity mechanism. We intend to show that the scientific and operational dimensions of wildfire management can be aligned to pursue shared objectives, regarding the increase of safety levels in local communities affected by large wildfires.

2. Materials and Methods

2.1. Study Area

Alvares is a civil parish located in the central region of Portugal, in the municipality of Góis, with a surface area of ca. 10,000 ha. It is integrated in a fire-prone region, with high fire frequency and area burned; in the sub-region *Pinhal Interior*, which also includes 19 other municipalities and covers a total area of 4520 km² (Figure 1), the burned area recorded since 1975 surpasses 7100 km². Some areas have burned 9 times in 40 years. In the last 10 years alone, about half the area of the sub-region was burnt (www.icnf.pt). Alvares is characterized by a complex topography, with elevation ranging roughly between 300 and 1200 m, and slopes above 20° are found on 38% of the parish area [51]. Regarding landcover, around 90% of the area is covered by continuous forest plantations, mainly composed of Tasmanian blue gum (*Eucalyptus globulus*) and maritime pine (*Pinus pinaster*).

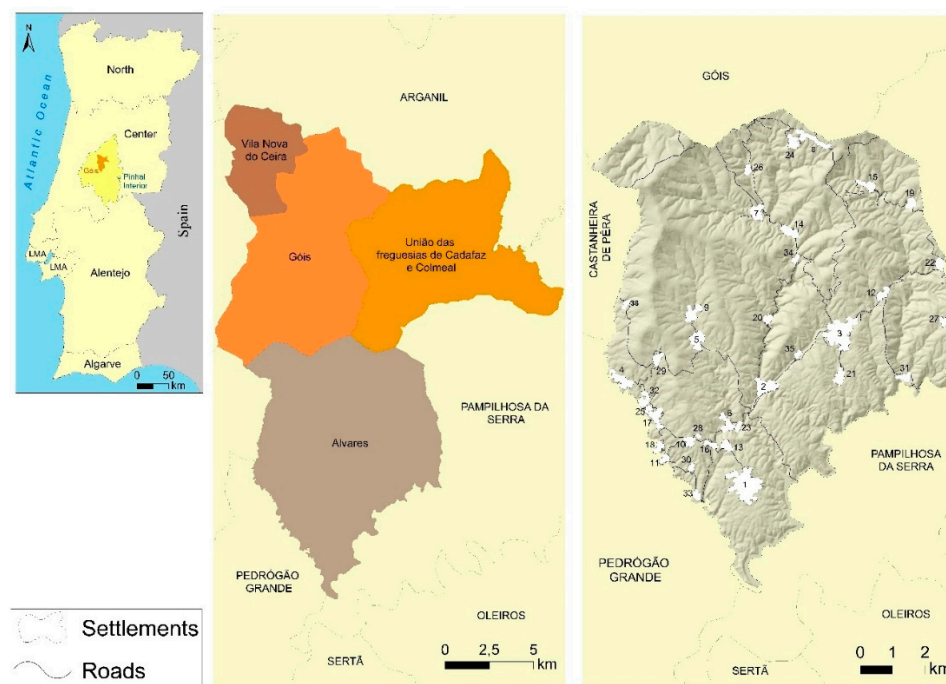


Figure 1. Location of the Alvares civil parish, in the south part of the Góis municipality, which belongs to the sub-region of Pinhal Interior, in central Portugal. On the right, the location of the 36 settlements in Alvares.

In the civil parish of Alvares, there are 812 inhabitants, 53% of whom are women, according to the latest census (2011) [52]. The demographic structure of the population is highly skewed, with only 12% of people under 20 years old, and 47% of people over 65 years old. More than a third of the residents only have elementary school education and 17% are illiterate, whereas less than 2% have an university degree. The economic structure of the parish is marked by a low percentage of active population (28%), the large majority working in the tertiary sector (56%). About 11% of the residents are unemployed and 53% are pensioners or retired.

There are 1662 buildings in Alvares, the large majority with a residential function. Around 76% were built before 1980 and 17% of the housing was vacant in 2011. In the framework of this research, field work was carried out in 2018 in the parish, which allowed to update the number of functional buildings (1634) and the number of people (799), as well as some of the sociodemographic characteristics of the residents.

2.2. Delimitation and Characterization of the Human Settlements in Alvares

We identified 36 settlements in the civil parish (Figures 1 and 2), which are recognized as hamlets or small villages by local population; as such, both terms are here used with equivalent meanings. We delimited the settlements based on the definition of “Lugar” by the National Institute of Statistics (<https://smi.ine.pt/Conceito/Details/2990>). A settlement is defined as a population cluster with at least 10 residential buildings, with spatial continuity and separated from other groups by more than 500 m. The perimeter of the settlements was established in the line of contact between the furthest buildings of each village and the forested or wildland areas nearby; the settlement can include the agricultural land surrounding the core of the residential cluster, in case it exists. One of the settlements identified is an exception, as it corresponds to a cluster of six non-residential buildings, but the number of people working there surpasses the number of inhabitants in most of the residential clusters. As such, the higher number of exposed people justified its integration as an individual spatial unit (Figure 2, nr. 13). In two other cases, the number of residential buildings is below 10, but they are sufficiently distant

from other groups, have a specific name, and both inhabitants and local authorities recognize them as distinct places (Figure 2, nr. 28, 36).

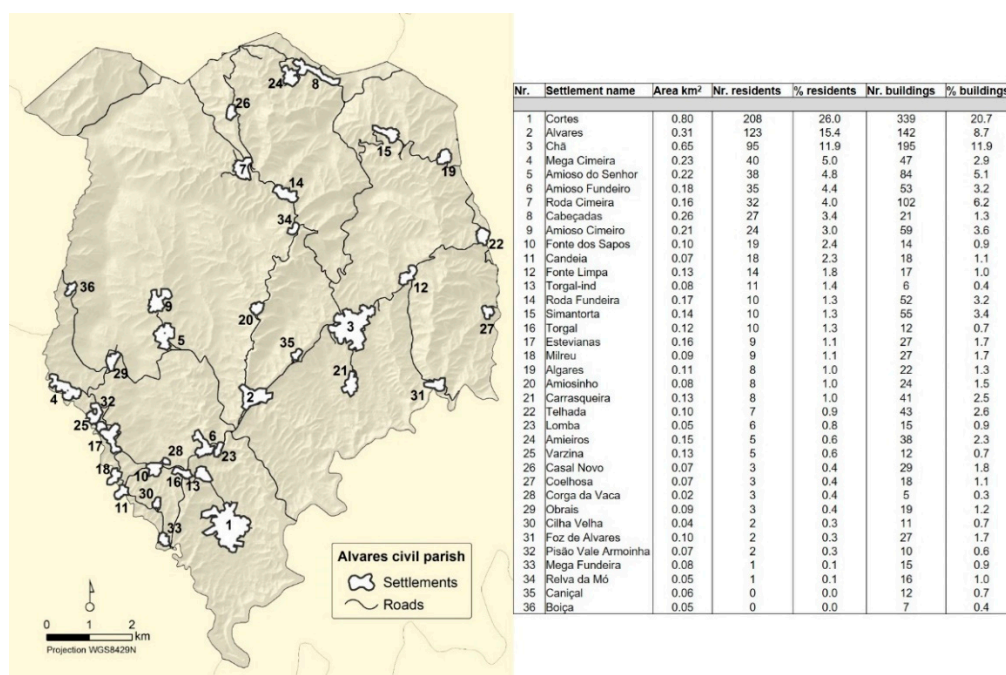


Figure 2. Settlements identified in the civil parish of Alvares and their main characteristics regarding area, residents, and buildings. The settlements are numbered in decreasing order of the number of inhabitants.

The area of the settlements ranges between 0.02 km² and 0.8 km², and the number of residents varies between 1 and 208, besides the two villages without permanent inhabitants (Figure 2, nr. 35 and 36), but where absent owners may return to for holidays, especially in summertime, when wildfire hazard is higher [27]. Less than 10% of the settlements (three of them) congregate 54% of the total population of the parish, whereas 31% have less than four residents. About 44% of these settlements do not have young people below 20 years of age, and in 22% of them, $\frac{3}{4}$ of the inhabitants are over 65 years old. We found people with a university degree only in seven settlements, and in 10 of them, at least half the people have only the elementary education level. Over 60% of the settlements have less than 30% of the economically active population, most residents being retired or pensioners. In 56% of the settlements, most buildings (> 75%) were built before 1980 and in nearly half of these, around one-third of the buildings are made of adobe walls or loose stone masonry with wooden structure.

2.3. Data Collection and Risk Analysis Procedure

The risk components of exposure and vulnerability were first assessed separately and aggregated afterwards in a 5-class risk index. Each component represents a specific dimension of the wildfire risk, requiring distinct data and tools. This allows integrating quantifiable variables at different steps, which can be translated into indicators and mapping tools. Each settlement was considered an individual spatial unit and the non-populated area was excluded, since the focus were the places where people and built-up structures spatially coincide within the civil parish.

2.3.1. Exposure

Exposure results from the combination of hazard levels with the exposed elements. Fire hazard was quantified by simulating the spread of wildfires in the landscape, using the Fire UNCertainty Simulation system (FUNC-SIM) developed in the scope of the project [53] by the Forest Research

Centre, School of Agriculture of the University of Lisbon (Portugal). FUNC-SIM simulates thousands of potential wildfires burning under historical meteorological conditions that were coincident with very large wildfires (VLW, >1000 ha). This threshold was selected based on the fire history of the civil parish, as 90% of the total burned area since 1975 was caused by 10 large fires above 1000 ha. Ignitions are randomly located based on a probability density surface estimated from historical ignitions that led to VLW. Fuel maps were derived from the Portuguese Land Use and Land Cover map [54], using the fuel model typology defined by Fernandes (2005) [55] to assign the corresponding fuel class. Uncertainty in the fuel model distribution was integrated in the simulations using a stochastic approach. This was important to estimate the impact of different management scenarios (described in Section 2.4), on the fuel distribution at the landscape-level, and consequently, on the fire hazard. The spread and behavior of each wildfire was simulated using the FARSITE simulation system (United States Department of Agriculture, Forest Service, Rocky Mountain Research Station) [56] at a 100 m spatial resolution. The simulated wildfires were combined into a burn probability map, defined as the percentage of times a given grid cell burned. The probability of a wildfire affecting a settlement was estimated as the percentage of times the cells in its vicinity were burned, assumed as the number of times a fire could reach any part of the settlement's perimeter, i.e., the interface between the built-up structures and forested area.

The exposed elements represent the people and buildings existing in the settlements of the parish, weighted by their importance or need of protection, as given by the municipal plans of defense against forest fires [57]. To calculate the exposed elements, population data were obtained from the latest census survey at the subsection level [52] (Table 1). The subsections are spatial units defined for statistical purposes that roughly correspond to the smallest populated places ("Lugar"), as defined beforehand. The number of buildings was obtained from a cartographic database at the municipal level and complemented with the statistical data available for the subsection (Table 1). When possible, these data were updated with fieldwork done during 2018.

Table 1. Variables used to calculate the different risk components and their data sources.

	Variable	Format	Resolution/Scale	Source
Exposure	Burn Probability (hazard)	Raster	1 ha	FuncSim, FARSITE
	Population density	Vector	Subsection	National Statistics (2011)
	Buildings density	Vector	Subsection	Field work (2018)
Vulnerability	% women	Vector	Subsection	National Statistics (2011)
	% young people (<20 years old)			
	% elderly people (>64 years old)			
	% illiterate people			
	% people with elementary school level			
	% people with secondary school levels			
	% people with university education			
	% unemployed people			
	% active working population			
	% people working in the primary sector			
	% isolated buildings			
	% buildings built until 1980			
	% buildings made of stone and adobe			
Coping Capacity	% vacant housing	Vector	1:25,000	DGT (2018)
	Land Use and Land Cover types			
	Digital Elevation Model			
	Road network			
	Individualized Buildings			
	Shelters (safe zones)			

Exposure was estimated as a combination of fire hazard and exposed elements, weighted based on the guidelines of the municipal plans of defense against forest fires currently in place, as follows:

$$\text{Exposure} = \text{BP} * [\text{norm}((\text{pd} * 1) + (\text{bd} * 0.75)) * 100] \quad (1)$$

where BP corresponds to the Burn Probability (Hazard level), pd represents the population density of each settlement (weighted by 1), bd represents the buildings density of each settlement (weighted by 0.75), and norm means the normalization according to the minimum and maximum values found within the parish, scaled in the range 0–100.

The values of exposure were classified into five categories, using the range of the normalized values to define the thresholds. The classes represent intervals of equivalent size with progressive increments in values.

2.3.2. Vulnerability

Vulnerability is assessed according to the sociodemographic characteristics of the population and their living conditions, which influence the potential for loss of the communities [9,35–37].

We collected data on gender, age groups, education levels, and working sectors, as well as data on building age, construction materials, and arrangement, at the subsection level, from the latest census [52] (Table 1). These variables were integrated in a hierarchical clustering analysis with Ward's method [58], to identify groups based on the (dis)similarities in the variables amongst the settlements. In this method, each settlement is initially considered an individual cluster and compared to the other settlements, one at the time. When another settlement is joined with the group, the mean and variance of the variables in the cluster are recalculated. The association of the new settlement with that cluster is determined by the sum of squared error (SSE) in relation to the group mean. Low SSE values indicate high similarity of the new settlement with the cluster. The process is repeated until all the settlements are tested and integrated in a cluster.

The analysis provided five different clusters that were matched with a specific vulnerability class, according to the values (mean, median, and maximum) of each variable and their relative position in relation to the other clusters. The variables were analysed in view of their influence in vulnerability levels, either positive when it decreases vulnerability, or otherwise negative. The vulnerability class was attributed according to the number of variables with negative and positive influence in each cluster, giving more importance to those representing population.

Coping Capacity

Coping capacity represents the ability to react to a wildfire event. It was incorporated as an additional factor of vulnerability, considering that a lower ability to respond will increase the potential for loss of exposed elements. Coping capacity was measured in two different dimensions: (i) the distance of each village to the fire station, representing the institutional capacity of rescue and emergency services; (ii) the time needed for people in each village to evacuate and reach a safe area (shelter), representing the ability for self-defence of residents.

The distance to the fire station was calculated considering the ground distance via paved roads, measured in metres, between the centroid of each village polygon and the nearest fire station building, which is located in the settlement of Alvares (Figure 2, nr. 2). All other fire stations located in adjacent parishes were farther away.

Regarding the time of evacuation to a shelter, we applied a pedestrian evacuation model based on GIS analysis obtained from the United States Geological Survey (USGS, Reston, Virginia), the Pedestrian Evacuation Analyst Tool (PEAT) [59,60]. Initially implemented in coastal communities potentially affected by tsunamis, this tool has also been recently applied to areas affected by landslides and debris flows [61,62]. Based on land cover types, topographic conditions, road network, and existing structures, this tool allows to define safe meeting spots and evacuation routes within a hazardous

territory, and the results are converted to mapping tools that wildfire managers can easily interpret. It uses slope directionality to calculate travel speed, with an anisotropic approach, i.e., walking downhill is faster than walking uphill. To implement this evacuation model, we first had to identify the safe areas within the settlements, in this case, an existing building that could be converted into a wildfire shelter. The shelters are considered the safe zones to where people must evacuate, whereas all the remaining territory, which is mostly forested area in this parish, is the Hazard Zone. We identified potential shelters in each village through field work carried out in 2018, according to the following criteria: (i) possibility to restructure the building in order to comply with fire safety rules; (ii) low fuels loads around the building and ability to implement fuel management over time; (iii) accessibility to the shelter building from all other locations in the village, preferentially public buildings such as community centres or chapels. These conditions are recommended by the Programme “Safe Villages, Safe People”, created in 2018 and currently being implemented in selected villages by local authorities and civil protection services. Since population density is low in these villages, the size of the building was not an issue. The other base layers were a Digital Elevation Model and a land use and land cover (LULC) map (Table 1). The LULC map was aggregated into nine categories, weighted by the speed-conservation value (SCV). The SCV represents the fraction of the maximum speed that could be achieved across a given landcover type [60,63]. Values range from zero (when travel is not possible) to 1 (when pedestrian evacuation speed equals the base travel rate), as shown in Table 2. The paved roads were given the SCV of 1, as they correspond to the preferable path. To estimate the time required to reach one of the safe zones (shelters) identified, the tool calculates the cost path based on a specific travel speed defined by the user. In this case, bearing in mind the high proportion of elderly people in the parish, we opted for a conservative approach and defined a speed of 1.03 m/s (approximately 3.7 km/h), considering the mean walking speed of people above 70 years old [64,65]. The model estimates the time required to reach the closest safe zone for each grid cell (at 5 m resolution) in the civil parish area, in minutes. The estimation for each settlement was retrieved from the maximum values found within the cells of each settlement, assumed as the maximum expected evacuation time (on foot) from the buildings in the village to the nearest shelter.

Table 2. Speed-conservation values (SCV) for the nine categories of land cover used in the Pedestrian Evacuation Analysis Tool. Values were based on the tool guidelines [60] and adjusted to the characteristics of the civil parish.

Class	SCV *	Rationale
Paved roads	1	Preferable path
Artificial surfaces	0.9091	Travel is easier and recommended
Pastures	0.6667	Travel is easier
Sparse vegetation	0.6667	Travel is easier
Agriculture	0.5556	Travel is possible, ease depends on farming type
Shrubland	0.2778	Travel is possible, a bit easier than forest but not advisable
Eucalyptus forest	0.1389	Travel is possible, but difficult and not advisable
Pine forest	0.1389	Travel is possible, but difficult and not advisable
Other forest	0.1389	Travel is possible, but difficult and not advisable
Water	0	No travel is possible

* Speed-Conservation Values (SCV) are listed by decreasing order.

Coping capacity was incorporated in vulnerability by adjusting the class initially given to the settlements. The settlements that were distant more than 8 km from the fire station and where people would simultaneously take more than 30 min to reach a shelter, were given the higher vulnerability

class that succeeded the original one. On the contrary, the settlements located less than 2 km apart from the fire station and with an evacuation time below 20 min, and those up to 5 km far from the fire station but with an evacuation time under 10 min, would change to the immediately lower vulnerability class, if available. The 20 min corresponds to the maximum time expected for the initial attack by the wildfire suppression services [66].

2.3.3. Wildfire Risk

Risk levels were obtained by multiplying the exposure and vulnerability classes (Figure 3). The final classification of risk followed a five-category scheme and considers that the very high class includes at least one of the components (exposure or vulnerability) in the highest class and the other component in either the highest or the second highest level. An equivalent approach was applied to define the very low class, whereas the intermediate and increasing values were progressively attributed to the other three classes. This risk classification ranks the existing settlements according to the probability that a wildfire may occur and affect them negatively.

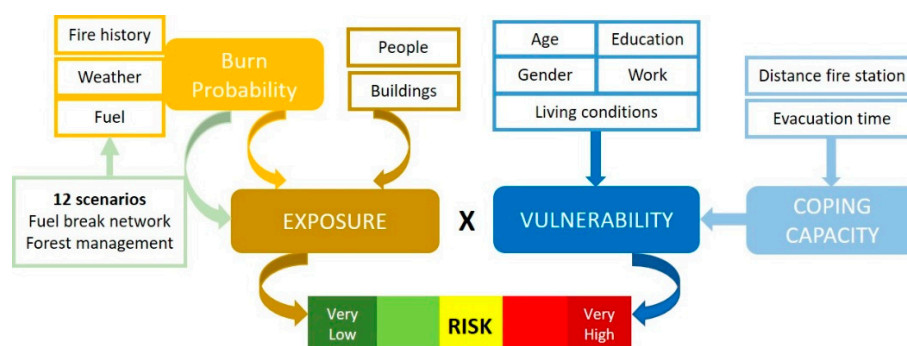


Figure 3. Schematic representation of the risk analysis procedure implemented. The variables used to estimate exposure and vulnerability are presented in Table 1. The 12 management scenarios are described in Section 2.4.

2.4. Landscape-Level Fuel Management Scenarios

We analyzed how different landscape-scale fuel management scenarios can change the level of exposure of each village to wildfires and, consequently, of risk. We expect that reductions in fuel loads and the creation of spatial discontinuities in the landscape will decrease the probability of a wildfire affecting a settlement, even when these interventions are defined with the general purpose of decreasing the incidence of large fires in the landscape, and not specifically to protect villages. Two types of scenarios were designed: (i) an increase in the level of forest management activities (Mngt) carried out by landowners that would result in lower fuel loads; (ii) a fuel break network (FBN) with different priorities and extent in the civil parish.

- (i) Forest management activities: Overall, 38% of the forest land of Alvares is intensively managed, which includes frequent fuel management (every five years), the use of genetically improved material and fertilization. About 50% of the land in the civil parish has a basic forest management, mainly limited to the tree-cutting process after the rotation period, whereas 10% of the forest land is not managed at all [49]. We considered two different levels of forest management, namely a moderate (~20%) and high (~30%) increase in managed forest area in the parish, besides the 38% already in place. The increase in forest management changes the distribution of fuels, decreasing their loads.
- (ii) Fuel break network (FBN): the implementation of a fuel break network is defined in the municipal plans of forest defense against wildfires, established by law since 2006 (Decree-Law 124/2006, of 28 June), and follows the technical guidelines of the National Forest Services. The network was designed with the specific function of protecting people, assets, and forested areas against

wildfires, considering the topographic and hydrographic conditions, the fire history of Alvares and neighbouring parishes, and the exposure of villages [53]. The creation of a FBN implies the creation of fuel discontinuities in the landscape, reducing fuel density in selected areas. In Alvares, the fuel breaks should be located in elevated areas, in the main ridges, to support also firefighting activities, and should be at least 125 m large. We considered three different levels of fuel break network implementation: first priority (1/3 of total extent), second priority (2/3 of total extent), and the entire network (Figure 4). Each level corresponds roughly to 450 ha of land. The first priority fuel breaks were designed with the purpose to decrease the area traveled by large fires, the second priority to protect roads, infrastructures and buildings, and the third priority to isolate potential fire ignition spots. In the FBN areas, specific land uses are promoted, to ensure low fuel loads: agricultural fields, pastures, shrubs managed every 3 to 5 years, possibly with broadleaved trees planted at least 3 m apart. These fuel break network options influence the distribution of fuel types and loads in the landscape, which is reflected in the burn probability simulations. It was assumed that, in the first year, the FBN areas do not have burnable fuels, progressively increasing the fuel load to low density/low height shrubs, up to the fifth year after their implementation, when they are managed again and the cycle restarts [49].

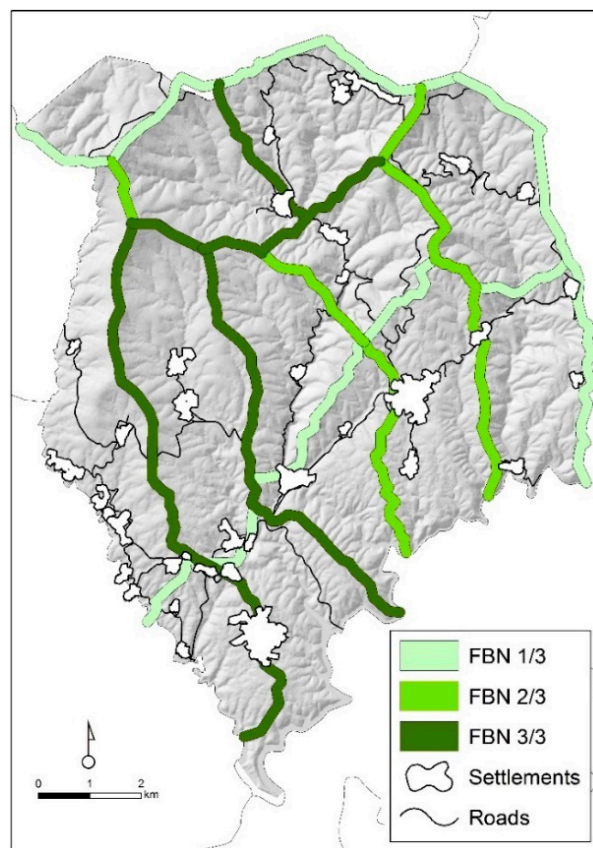


Figure 4. Fuel break network (FBN) planned for Alvares, in the three priority levels: FBN 1/3 (first priority, to decrease the area traveled by large fires), FBN 2/3 (second priority, to protect buildings and infrastructures), FBN 3/3 (third priority, to isolate potential fire ignition spots).

Additionally, we considered a Business-as-Usual (BAU) scenario, equivalent to the pre-2017 settings, without any increase in forest management and/or implementation of fuel breaks. All these types of fuel management options were combined, resulting in a total of 12 scenarios (Table 3).

Table 3. Scenarios tested regarding current conditions (Sc0), level of forest management activities (Sc1–Sc2), fuel break network implementation (Sc3–Sc5), and possible combinations between fuel break and forest management (Sc6–Sc11).

Code	Scenarios	Fuel Break Network	Forest Management
Sc0	Current scenario (BAU)	No implementation	Low (38%)
Sc1	Scenario Mod_Mngt	No implementation	Moderate (+20%)
Sc2	Scenario High_Mngt	No implementation	High (+30%)
Sc3	Scenario FBN_1/3	Implementation of first priority (1/3)	Low (38%)
Sc4	Scenario FBN_2/3	Implementation of first and second priority (2/3)	Low (38%)
Sc5	Scenario FBN_3/3	Full Implementation, all priorities (3/3)	Low (38%)
Sc6	Scenario FBN_1/3_Mod_Mngt	Implementation of first priority (1/3)	Moderate (+20%)
Sc7	Scenario FBN_1/3_High_Mngt	Implementation of first priority (1/3)	High (+30%)
Sc8	Scenario FBN_2/3_Mod_Mngt	Implementation of first and second priority (2/3)	Moderate (+20%)
Sc9	Scenario FBN_2/3_High_Mngt	Implementation of first and second priority (2/3)	High (+30%)
Sc10	Scenario FBN_3/3_Mod_Mngt	Full Implementation, all priorities (3/3)	Moderate (+20%)
Sc11	Scenario FBN_3/3_High_Mngt	Full Implementation, all priorities (3/3)	High (+30%)

We first calculated the level of exposure of each settlement for the BAU scenario (Table 3, Sc0). To evaluate the effects of the different management options, we estimated the differences in the proportion of settlements in the exposure classes between each potential scenario (Table 3, Sc1 to Sc11) and the BAU scenario (Table 3, Sc0). We anticipated that the scenarios with higher level of forest management and more extensive implementation of the fuel break network would reduce the number of settlements in the higher exposure classes, since burn probability would likely decrease. The effect of the different scenarios in risk classes was also assessed, as changes in exposure levels can influence the risk classification, although vulnerability levels remain always the same.

3. Results

3.1. Exposure

In the BAU scenario, the values of burn probability for the settlements ranged between 12% and 34%. The settlements located in the northeast sector of the parish had a higher burn probability, mostly due to historical ignition patterns and meteorological conditions [53]. The probability that a large fire could reach the perimeter of the villages was above 20% for half of them, whereas 17% of the settlements showed a burn probability above 25%.

When combined with the exposed elements, the three largest settlements show very high exposure, since these are the places where more people and buildings can be affected (Figure 5A). On the contrary, the settlements located in the southwest sector of the parish predominantly belong to the lowest classes of exposure, a pattern resulting from the combination of low density of exposed elements with a low burn probability. Overall, 41% of the settlements are classified with low and very low exposure, 28% of

villages are in the high and very high classes and the intermediate class includes 31% of the villages in the parish.

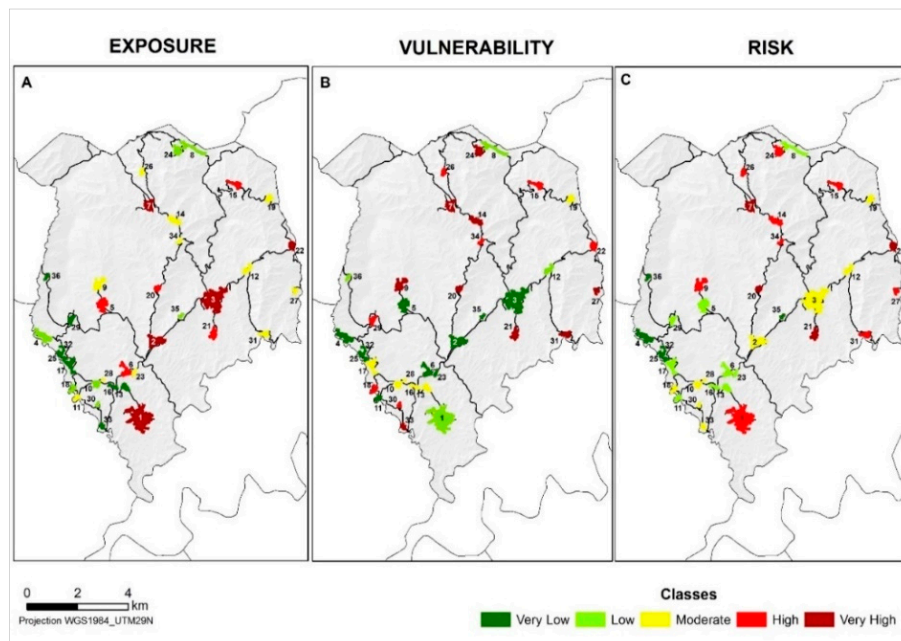


Figure 5. Classes of exposure (A), vulnerability (B), and risk (C) in the BAU scenario (Sc0) for the settlements of the civil parish of Alvares.

3.2. Vulnerability and Coping Capacity

The highest vulnerability class was attributed to the cluster of villages with the highest number of variables with a negative influence (increasing vulnerability) and the lowest number of positive ones. This corresponds to the settlements that have the highest mean proportion of elderly, women and illiterate people, with no people with university education and the highest proportion of vacant housing. Conversely, the lowest vulnerability class corresponds to the cluster of villages with the lowest mean proportion of elderly and the highest mean proportion of young people, although still rather low, as well as the highest proportion of active population and of people with secondary education (Figure 6).

Regarding the coping capacity, 25% of the settlements are more than eight km away from the nearest fire station, and these are located in the north sector of the parish (Figure 7). Evacuation times are short, below 10 min, for the settlements where a potential shelter exists, which were identified in half of the villages (Figure 7). Settlement 8 is an exception, since its buildings spread longitudinally along a road and some are farther away from the shelter identified, although still below 20 min. There are four settlements (11%) where the evacuation time surpasses 1 h and eight others (22%) where people would take at least 30 min to reach a shelter. In both these situations, no potential shelter was identified amongst the existing buildings and people would have to walk to the nearest village where one exists.

Variables	Cluster1 Class2	Cluster2 Class5	Cluster3 Class1	Cluster4 Class4	Cluster5 Class3	Influence vulnerability
elderly	46	79	16	67	43	↑
women	56	61	47	45	51	↑
young	14	0	21	2	13	↓
illiterate	12	37	19	5	30	↓
elementary educ	34	27	30	83	40	↑
secondary educ	7	1	11	2	0	↓
university educ	1	0	1	2	0	↓
active pop	31	6	48	6	26	↓
unemployed	9	0	3	0	44	↑
primary sector	16	0	3	0	0	↑
build isolated	57	67	80	71	89	↑
build pre-1980	75	75	86	81	75	↑
build stone adobe	9	26	34	23	25	↑
vacant housing	10	31	16	17	6	↑

Very Low Low Moderate High Very High
 ↑ Negative influence, increases vulnerability
 ↓ Positive influence, decreases vulnerability

Figure 6. Mean values (%) of the variables in each cluster. Colours represent the vulnerability class that should be attributed to the cluster, considering the relative position of the values in comparison with the other clusters and the influence of the variable in vulnerability levels. The final class (1 Very Low to 5 Very High) was defined according to the number of variables with a negative or positive influence in vulnerability level, for each cluster.

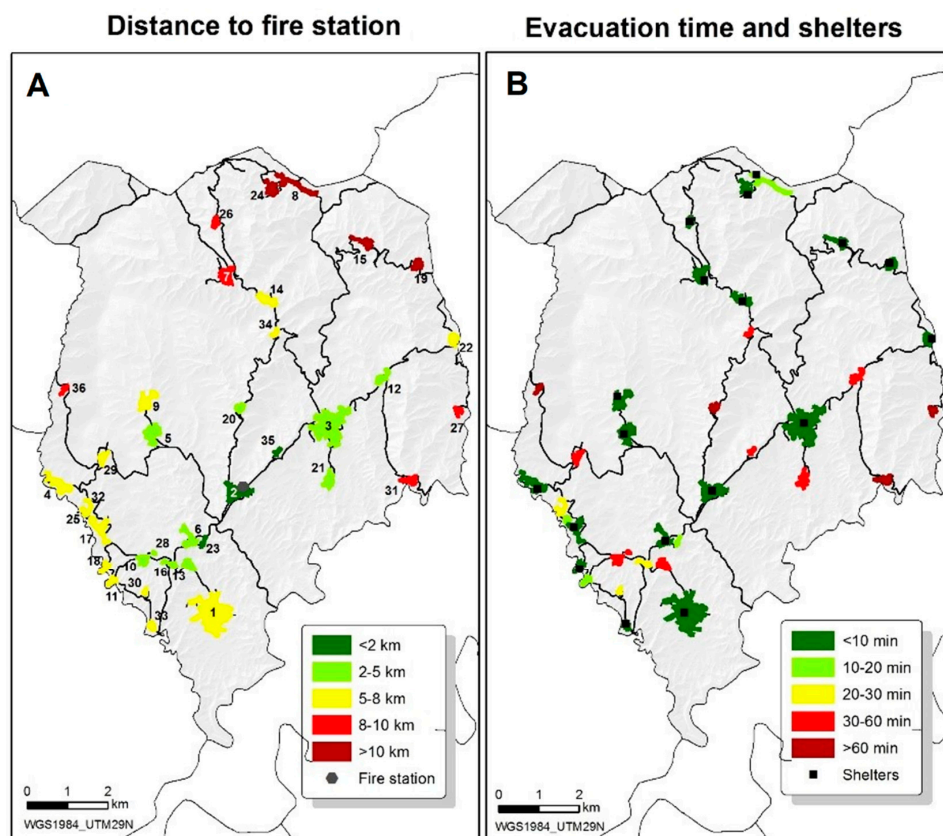


Figure 7. Variables regarding response capacity per settlement of the civil parish of Alvares: distance to the nearest fire station, in km (A) and evacuation time, in minutes (B).

The integration of the clusters analysis and the coping capacity shows a predominance of the high and very high vulnerability classes, with 44% of the settlements in total, whereas the two lowest

vulnerability classes include 39% of the settlements. The spatial patterns differ from exposure; overall, the settlements with higher vulnerability are not those with higher exposure, as seen in the three largest villages (Figure 5B).

3.3. Wildfire Risk

We found that 11% of the settlements had a very high wildfire risk, adding to the 25% in the second higher risk class. The Low and Very low classes gathered 39% of the villages, most of them located in the southwest area of the parish (Figure 5C). The three largest villages have either an intermediate or high risk, mainly due to exposure levels, rather than vulnerability, which is low or very low. Five of the settlements (14%) have a high or very high level regarding all three aspects, i.e., exposure, vulnerability, and risk, (Figure 5, villages 7, 15, 20, 21, 22), indicating problems in all three dimensions.

3.4. Effects of Fuel Management Scenarios in Exposure and Risk Levels

The implementation of any of the fuel management scenarios would decrease the hazard and exposure levels. Considering only villages with high and very high exposure, where mitigation measures should be prioritized, moderately increasing the managed forest area (Figure 8A, Sc1) would reduce the proportion of exposed settlements by 32% when compared with the BAU scenario (Figure 8A, Sc0). The same effect would be obtained with the implementation of the top priority segments of the FBN without increasing forest management (Figure 8A, Sc3). If the FBN is implemented by 2/3 (Figure 8A, Sc3) or completely (Figure 8A, Sc5), the reduction in exposure is higher, progressively decreasing the highly exposed villages to 14%, which corresponds to a reduction of 50% when compared with the BAU scenario. If the fuel break implementation is combined with an increase in forest management, the decline of exposure is even higher, particularly when the full implementation of the FBN is done jointly with a high increase in forest management (Figure 8A, Sc11). In this case, the villages with high and very high exposure would decrease to 11%, a reduction of 61% in relation to the current conditions (Figure 8A, Sc0).



Figure 8. Percentage of settlements with high and very high exposure (A) and risk (B) in the different scenarios. In both A and B, the x-axis represents the three levels of forest management, and the coloured lines represent the fuel break network implementation with different priorities. A—Exposure, represents the combination of burn probability (hazard) with exposed elements; B—Risk, represents the combination of exposure and vulnerability (with coping capacity).

The impact of the different forest management scenarios in wildfire risk is less pronounced. The increase in forest management to any other level and without FBN implementation (Figure 8B, Sc2 and Sc3), can reduce villages at risk by 8%. If FBN is implemented without a change in forest management, the maximum reduction expected is of 14%, decreasing the proportion of settlements with high and very high risk to 31% when FBN is fully implemented (Figure 8B, Sc5). When FBN full implementation

is combined with high forest management (Figure 8B, Sc11), the proportion of villages at high risk is reduced by 22% in relation to the current conditions.

The classification of the settlements in relation to exposure and risk in each scenario is presented as a colored heatmap in Figure 9. The risk classes are more homogeneous across the several scenarios, since they depend on exposure as much as on vulnerability and this component remains unchanged in all scenarios. Settlements 7 and 22 belong to the high or very high classes in all scenarios, whereas settlements 25, 35, and 36 are the least exposed and vulnerable across all landscape-level fuel management options.

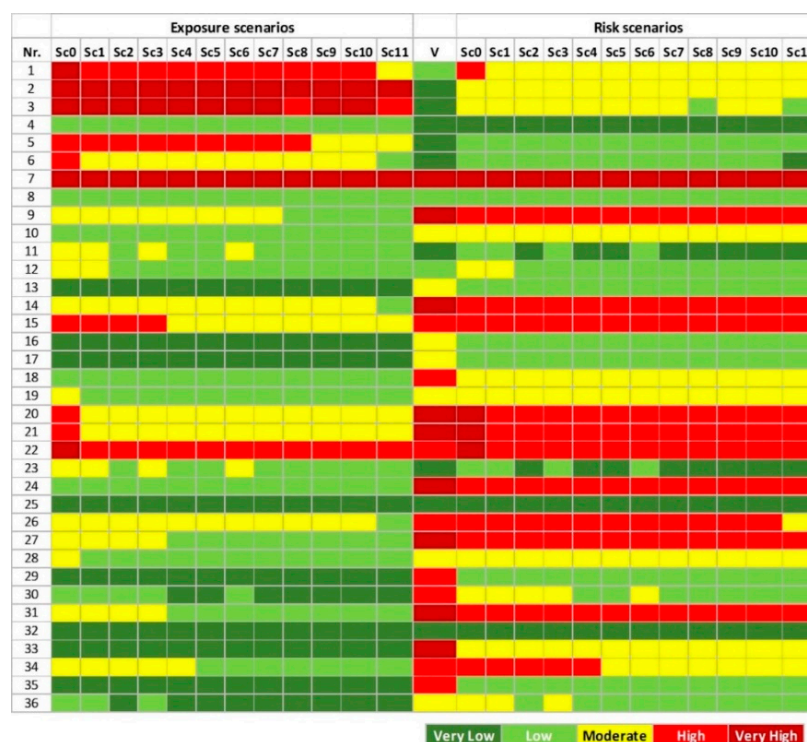


Figure 9. Heatmap with coloured classes for the risk components (exposure; V-vulnerability; risk) in each settlement, considering the different scenarios (Sc0–business-as-usual, to Sc11–high forest management combined with the full implementation of a fuel break network. See Table 3 for details).

4. Discussion

4.1. Risk Assessment at the Settlement Scale

In this research, we applied a wildfire risk assessment procedure to a civil parish of central Portugal, focused on the safety of people and assets assembled in 36 small settlements. Our results provide a ranked classification of these small villages, with over a third having high or very high risk. This assessment resulted from the combination of different components, which represent specific dimensions of wildfire occurrence: hazard, exposure, and vulnerability. The stepwise procedure is based on prior studies [67–70] although it was carried out at a finer spatial scale. Fire simulations were used to estimate the probability that large wildfires, over 1000 ha, could reach the perimeter of each settlement. Simulation approaches have been applied to estimate wildfire exposure of particular assets, such as cultural heritage sites, residential areas, energy infrastructures or natural habitats, specifically in Sardinia, Italy [71]; in Navarra, Spain [41]; and in Chalkidiki, Greece [72]. Similar methods have also been applied to estimate communities exposure in the USA [10,16]. In Alvares parish, large fires are expected to occur mainly in the north and east sectors of the parish and the settlements located in those areas, particularly those with higher density of people and buildings, have high or very high exposure levels, which was found for 28% of the villages.

The settlements with higher exposure do not necessarily have the highest vulnerability. For most villages, the aggregation of these two separate components tended to smooth the level of risk, with one dimension counteracting the other. Regarding vulnerability, nearly half of the settlements had high and very high vulnerability, derived from the sociodemographic conditions of resident population. Women, who predominate in the parish, are vulnerable elements due to their social role [9,73], a trend particularly relevant in older generations; women's household and family responsibilities kept them away from paid occupations, reducing their financial capability and their access to other opportunities, such as higher education, better jobs, or even a driving license. Overall, gender differences are smoothed in younger generations, but in the aging population of this parish, and across the inner areas of northern and central regions of Portugal, this reality still persists. Age is also a factor of vulnerability, as both the very young and the elderly lack the capability to react to an emergency, have low autonomy, and few resources to implement protective measures [9,18,37,74]. Education levels are reflected in the ability to understand and comply with prevention and safety regulations, in the level of risk perception, and in the access to qualified jobs that could improve their financial capacity [9,30,73]. People who work in the primary sector may be directly and severely impacted by wildfires, losing resources and financial security, and the unemployed lack the financial resources to maintain proper living conditions and to implement protection measures [9,35].

Buildings age and construction materials influence the resistance of the structures to fires [75] and reflect the living conditions of residents. Older buildings can have structural weaknesses and use materials less resistant to fire, as is the case of buildings made of stone masonry and adobe with a wooden structure. In Alvares, buildings constructed before 1980 predominate, when stricter construction rules regarding fire safety were not yet implemented. In addition, nearly one-fifth of the existing buildings are vacant and maintenance can thus be affected, because absent owners are less willing to implement protection and mitigation measures [76].

The use of the settlement as the spatial unit in risk analysis is a novel approach in Portugal, which allowed identifying the villages with higher exposure, vulnerability, and risk in a straightforward manner. Other assets besides human settlements can be included in the analysis, and the procedure can be replicated in other parishes, being particularly useful to local authorities, for the timely planning of safety protocols and mitigation measures adjusted to the circumstances of each settlement. Burn probability simulations can also be adjusted to incorporate weather parameters obtained from climate change scenarios, to obtain future estimations.

4.2. Effects of Fuel Management Options in Exposure and Risk Levels of Settlements

Wildfire exposure can be directly modified by the implementation of fuel management measures at the landscape-scale. Our findings show that, in all the scenarios, the proportion of villages with high and very high exposure would decrease with respect to the business-as-usual scenario, although at different levels. If the fuel break network were fully implemented and combined with widespread forest management, the reduction in highly exposed villages could reach 60%. These effects are somewhat expected, considering that any of the options tested would change the fuel distribution in the landscape, and therefore also the probability that a wildfire would reach a given settlement. Previous studies have shown that landscape interventions based on fuel management and different treatment intensities could reduce the average exposure of human assets to wildfires [77,78]. These fuel treatments can have positive effects in reducing communities exposure even when implemented distant from the settlements [79], except in severe wildfires under extreme weather conditions [80–82], when clearing the immediate surroundings of built-up structures would likely be more efficient. Fuel treatments can reduce wildfire exposure of human assets even when they are implemented with different purposes [83].

In the case in Alvares, fuel break implementation and forest management scenarios were designed with the general purpose of reducing fuel loads to create spatial discontinuities at the landscape-level. These were expected to reduce fire spread, create fire suppression opportunities and prevent the

occurrence of future large fires, and still all of the scenarios would have positive effects in the protection of villages. The choice of the fuel management strategy best suitable to manage large wildfires and reduce impacts to human communities, will also depend on social, legal, economic and land ownership constraints [84,85]. The reduced size of forest properties, which in Alvares is on average 0.5 ha [49], the lack of cadastre records in the country and the high absenteeism of landowners, who migrated to other regions or received the land as legal inheritance and are, therefore, detached from the community, are some of the challenges people have to face in these low-density regions [50]. A balance must be reached between multiple, sometimes competing objectives, since conservation or economic purposes may conflict with fuel treatments options required to reduce fire hazard [86,87]. Our findings indicate that the most efficient approaches will likely result from the combined application of different measures, and these could be further adjusted to the characteristics of the different settlements. Further work is needed to assess if the effectiveness and efficiency of fuel management options, in decreasing wildfire exposure and risk, would increase if they were designed with the specific purpose of protecting the human settlements.

4.3. Improving Preparedness and Defining Safety Interventions Within Settlements

The vulnerable circumstances of residents cannot be changed with fuel treatments nor with forest management strategies, but protective measures can be implemented to increase people's coping capacity and the resistance of built-up structures. Wherever old people or residents with low mobility options prevail, a safe shelter on-site is a reasonable possibility [20,24,25,88]. According to the criteria defined, half the villages within the parish did not have a building that might be transformed into a shelter, but a new structure could be built specifically for that purpose, to ensure each human settlement has a safe zone within its boundaries and to reduce evacuation times. This is one of the options advocated in the programme, "Safe villages, safe people", and the decision is made by the local authorities and civil protection services. In the case of Alvares, leaving the village is hindered by the time required to reach other settlements, which can take more than one hour on foot, and most residents lack other mobility means. However, different evacuation options should be investigated, considering other possible paths and transport means. Knowing the time needed to reach a safe spot by different alternatives, while taking into consideration the level of risk of each village, can help defining priorities for emergency intervention, as well as establishing safety and evacuation protocols adapted to each village. When the parish was struck by the wildfire in mid-June 2017, the firefighters and local authorities evacuated some of the villages and gathered people in the Alvares settlement, but since no compulsory evacuation system is in place in Portugal, the efficiency of this strategy depends on the willingness of the residents and on the capacity of the authorities. In severe wildfire conditions, which are expected to increase due to climate change, institutional and suppression capacities will likely be overridden [3,89–91]. For these reasons, fire management approaches must integrate strategies to improve community preparedness and people's coping capacity, tailored to their needs and abilities, to enable a suitable adaptation to fire-prone environments.

5. Conclusions

The recent large wildfires that affected Portugal in 2017, which caused the highest losses ever recorded in the country, have fostered multidisciplinary initiatives with the purpose of increasing the resilience of affected areas to large wildfires. In this research, we developed one such initiative in a civil parish of central Portugal, focused on the existing human settlements. Risk assessment was applied at the settlement scale and allowed to identify those villages that are either more exposed, vulnerable or at-risk of large wildfires, and that that will require priority interventions. The results of the different components of the risk assessment can be provided as mapping tools that could help the decision-making of fire managers regarding the timely application of prevention, mitigation, and emergency actions. In face of the expected worsening of wildfire risk due to climate change, both the self-defence and the institutional capacities need to be enhanced.

Our results have shown that risk levels depend on different combinations of exposure and vulnerability, and therefore actions to reduce risk should be tailored case to case. In addition, wildfire risk management cannot be disconnected from regional development and land-use planning policies in low-density regions, where Alvares is included. The sharp demographic decline and the aging of population, together with the reduction of farming activities and the subsequent land abandonment, make it imperative to find a suitable territorial vocation, perhaps different from before, but capable of creating more economic value and promoting the management of the land in a more effective and sustainable way, thus also reducing the risk of wildfires.

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